

# Early ultraviolet signatures from the interaction of Type Ia supernova ejecta with a stellar companion

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Accepted 2015 September 3. Received 2015 August 24; in original form 2015 July 21

## ABSTRACT

The progenitors of Type Ia supernovae (SNe Ia) are not yet fully understood. The two leading progenitor scenarios are the single-degenerate (SD) scenario and the double-degenerate scenario. In the SD scenario, the collision of the SN Ia ejecta with its companion star is expected to produce detectable ultraviolet (UV) emission in the first few days after the SN explosion within certain viewing angles. A strong UV flash has recently been detected in an SN 2002es-like peculiar SN Ia iPTF14atg by Cao et al., which is interpreted as evidence of an early-time UV signature due to SN ejecta interacting with its companion star, supporting the SD scenario. In this paper, we present the expected luminosity distributions of early-time UV emission arising from SN Ia ejecta-companion interaction by performing binary population synthesis calculations for different progenitor systems in the SD scenario. Our theoretical predictions will be helpful for future early-time observations of SNe Ia to constrain their possible progenitors. Assuming the observed strong UV pulse of iPTF14atg was indeed produced by the SN ejecta-companion interaction, our population synthesis model suggests that the progenitor system of iPTF14atg is most likely a red-giant donor binary system, and it is unlikely to have been a main-sequence or helium-star donor system.

**Key words:** supernovae: general - binaries: close - stars: evolution

## 1 INTRODUCTION

Type Ia supernovae (SNe Ia) play a fundamental role in astrophysics. The use of SNe Ia as cosmic distance indicators has led to the discovery of the accelerating expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999; Leibundgut 2008). However, the nature of SN Ia progenitors and the physics of the explosion mechanism remain mysterious (see e.g. Hillebrandt & Niemeyer 2000; Maoz, Mannucci & Nelemans 2014, for a review). It is generally accepted that SNe Ia arise from thermonuclear explosions of white dwarfs (WD) in binary systems (Hoyle & Fowler 1960; Finzi & Wolf 1967; Nomoto 1982). Depending on the nature of the companion star, the most favored progenitor models of SNe Ia are classified into two general categories, the single-degenerate (SD) scenario (e.g. Whelan & Iben 1973) and the double-degenerate (DD) scenario (Iben & Tutukov 1984; Webbink 1984).

In the DD scenario, two carbon-oxygen (CO) WDs spiral in and merge due to gravitational wave radiation, resulting in a single object with a mass near the Chandrasekhar limit, which may then explode as an SN Ia (Iben & Tutukov 1984; Webbink 1984). Although the DD channel has been suggested to lead to an accretion-

induced collapse rather than a SN Ia (Nomoto & Iben 1985; Saio & Nomoto 1998), several hydrodynamical studies of mergers of DD systems have concluded that some DD pairs can explode as SNe Ia (Rasio & Shapiro 1995; Fryer et al. 2010; Pakmor et al. 2010, 2011; Dan et al. 2011; Moll et al. 2014; Raskin et al. 2014). In particular, Pakmor et al. (2012) showed that the violent merger of two CO WDs with masses of  $0.9 M_{\odot}$  and  $1.1 M_{\odot}$  can lead to events that reproduce the observational characteristics of normal SNe Ia.

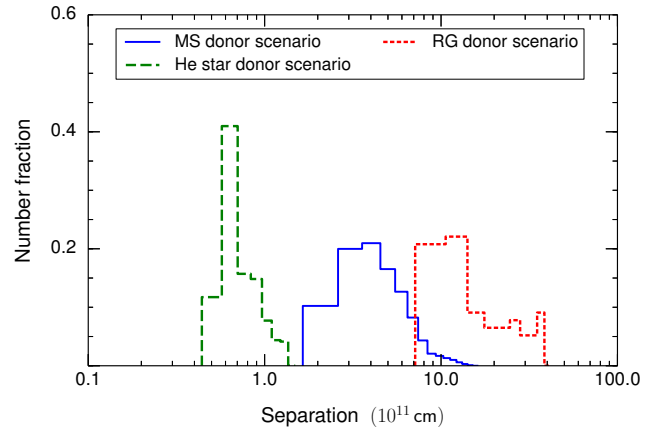
In the SD scenario, a WD accretes material from its non-degenerate companion star, where the companion star could be either a hydrogen (H)-rich star such as a main-sequence (MS), a slightly evolved sub-giant (SG) star or a red giant (RG) star, or a helium (He) star. When the mass of the WD approaches the Chandrasekhar-mass limit, it explodes as an SN Ia (e.g. Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004). In the H-accretion scenario, only a fairly narrow range in the accretion rate above  $10^{-7} M_{\odot} \text{ yr}^{-1}$  is allowed in order to attain stable H burning on the surface of the WD, avoiding a nova explosion. This makes the SD scenario difficult to explain the observed SN Ia rate (Han & Podsiadlowski 2004; Mannucci 2005; Wang et al. 2009; Wang & Han 2012; Maoz & Mannucci 2012). However, hydrodynamical simulations have shown that thermonuclear explosions of Chandrasekhar-mass WDs can reproduce some observational char-

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acteristics of either subluminous Type Iax supernovae (SNe Iax) (Jordan et al. 2012b; Kromer et al. 2013, 2015; Fink et al. 2014), or normal SNe Ia (Gamezo, Khokhlov & Oran 2005; Seitenzahl et al. 2013), or overluminous SNe Ia (Plewa, Calder & Lamb 2004; Meakin et al. 2009; Jordan et al. 2012a), which depend on the ignition conditions of a Chandrasekhar-mass WD.

On the observational side, more and more evidence seems to favor the DD scenario, e.g., the non-detection of pre-explosion companion stars at the location of SNe Ia (Li et al. 2011; Bloom et al. 2012), the absence of H features in the nebular spectra of SNe Ia (Leonard 2007; Lundqvist et al. 2013, 2015; Shappee, Kochanek & Stanek 2013), the lack of radio and X-ray emission around peak brightness (Li et al. 2011; Bloom et al. 2012; Brown et al. 2012a; Chomiuk et al. 2012; Horesh et al. 2012; Margutti et al. 2012), and the absence of a surviving companion star in SN Ia remnants (Kerzendorf et al. 2009; Schaefer & Pagnotta 2012). All this evidence supports the DD scenario although most of them can also probably be explained by the so-called “spin-up/spin-down” SD model (Di Stefano, Voss & Claeys 2011; Justham 2011). In the “spin-up/spin-down” scenario, the fast spin of the WD can increase its critical explosion mass to be higher than the maximum mass achieved by the WD, leading to the WD must spin down before it can explode (Di Stefano, Voss & Claeys 2011; Justham 2011). As a result, the donor star might shrink rapidly before the WD explosion, because it would exhaust its H-rich envelope during a long spin-down timescale of the rapidly rotating WD until the SN Ia explosion. In such cases, the companion star probably evolves to be a WD when the SN Ia explodes, which may explain the lack of H in late spectra of SNe Ia and the absence of a surviving companion in the SN remnants (Di Stefano, Voss & Claeys 2011; Justham 2011; Hachisu et al. 2012). On the contrary, some observations (Patat et al. 2007; Sternberg et al. 2011; Dilday et al. 2012) have detected signatures of H-rich circumstellar material (CSM) that are expected to exist around SNe Ia as the result of mass transfer from the companion, as well as WD winds (Nomoto 1982; Hachisu et al. 1999). This supports the SD scenario. However, this detected abundant CSM is in conflict with the missing radio signal for other SN Ia events, e.g. SN 2011fe (Chomiuk et al. 2012; Horesh et al. 2012). Also, some studies suggest that CSM can also form in the DD scenario (Shen, Guillochon & Foley 2013; Soker et al. 2013).

After the SN Ia explosion in the SD scenario, the SN ejecta expands freely for a few minutes to hours and then interacts with its non-degenerate companion star. As a result, the outer layers of the companion star are partially stripped and ablated while the star is shocked by the SN impact. Finally, the star survives the SN explosion and may show some peculiar features such as overluminosity or heavy element enrichment (Wheeler, Lecar & McKee 1975; Marietta, Burrows & Fryxell 2000; Pakmor et al. 2008; Liu et al. 2012, 2013a,b; Pan, Ricker & Taam 2012; Maeda, Kutsuna & Shigeyama 2014). The interaction of SN Ia ejecta with its companion star not only affects the star but also the SN itself. Kasen (2010) showed that the strong emission arising from the collision of SN Ia ejecta with its companion star in a SD progenitor system should be detectable in the first few hours to days after the SN explosion under favorable viewing angles. This strong emission is expected to alter the SN light curves at early times (Kasen 2010; Brown et al. 2012a; Cao et al. 2015; Moriya, Liu & Izzard 2015; Olling et al. 2015). Compared to the brightness of the SN itself at early times, such strong emissions should be brightest in the ultraviolet (UV). Therefore, early UV observations are proposed as a direct way to test progenitor models



**Figure 1.** Distributions of binary separations at the moment of SN explosion in different SD progenitor scenarios.

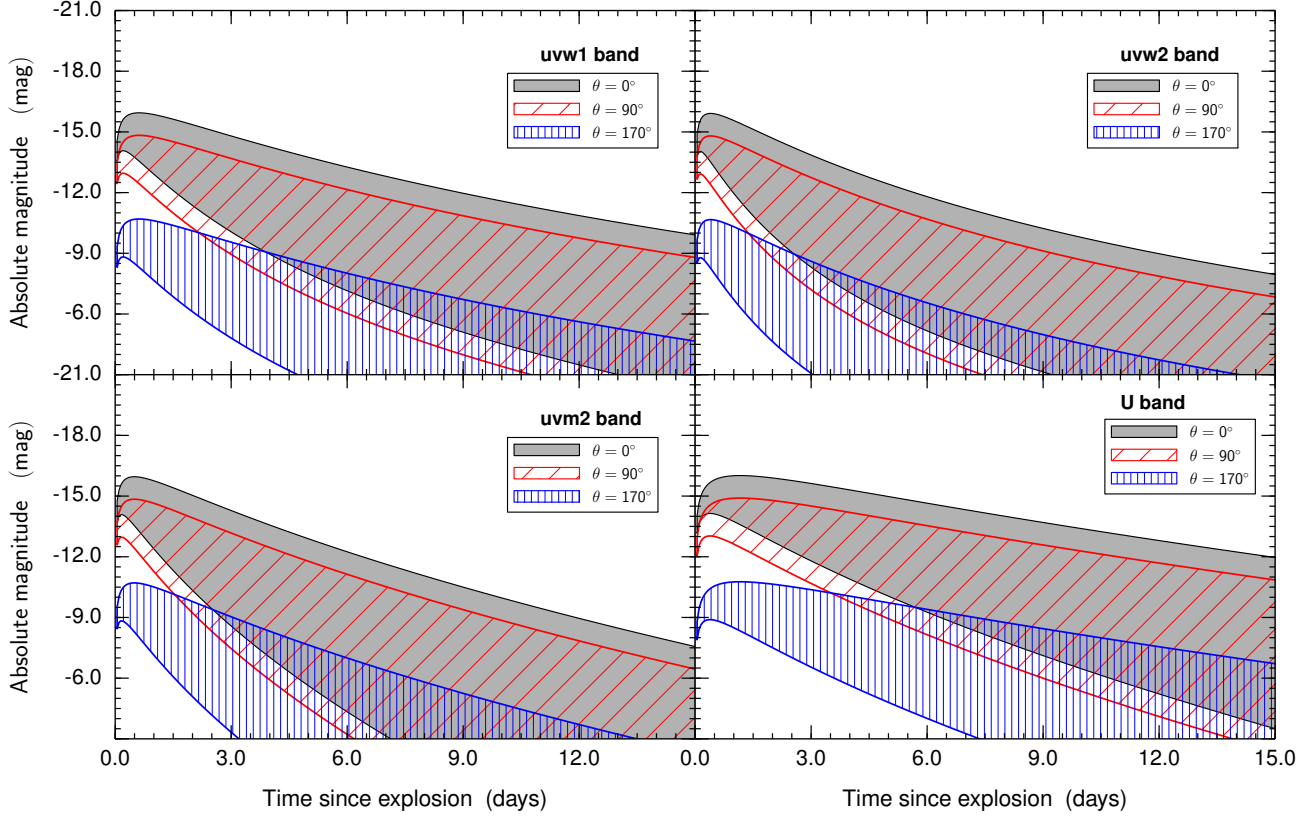
of SNe Ia. Following the analytical method of Kasen (2010), analysis of observed early light-curves of SNe Ia has been carried out by different groups to look for evidence of shock emission and thus constrain possible progenitors of SNe Ia (Hayden et al. 2010; Brown et al. 2012a,b; Cao et al. 2015; Olling et al. 2015). Most interestingly, a strong UV flash after the SN explosion has recently been detected from early-time observations of a peculiar subluminous SN Ia iPTF14atg by Cao et al. (2015). They further interpreted this early UV flash as strong evidence of excess luminosity produced by SN ejecta interaction with its companion star, and suggested that some SNe Ia arise from the SD scenario (Cao et al. 2015).

In this work, we use binary population synthesis (BPS) models for different progenitor systems of SNe Ia in the SD scenario to obtain the progenitor properties at the moment of SN Ia explosion, e.g., the companion radius ( $R$ ) and the binary separation ( $a$ ). We then put these progenitor parameters into the analytical model of Kasen (2010) to predict the distributions of early UV luminosity arising from the SN ejecta interacting with its companion star. Comparing our theoretical predictions with future early observations of SNe Ia will be helpful to constrain their possible progenitors. In addition, assuming the strong UV flash detected in iPTF14atg was indeed produced from the SN ejecta-companion interaction, we put further constraints on the progenitor system of iPTF14atg based on our BPS results.

The paper is organized as follows. In Section 2, we describe the BPS method used in this work. Theoretical early UV emission of SN ejecta-companion interaction are calculated in Section 3. In Section 4, we compare our predictions with the early-time observations of iPTF14atg and some discussions are presented. Our conclusions are summarized in Section 5.

## 2 BINARY POPULATION SYNTHESIS CALCULATIONS

Adopting the method described in Han & Podsiadlowski (2004), we have performed BPS calculations for the SD Chandrasekhar-mass scenario of SNe Iax by considering different types of companion stars in Liu et al. (2015). With that BPS calculation, we have obtained the distributions of progenitor properties of different SD binary systems at the moment of SN explosion although we assumed all Chandrasekhar-mass CO WDs would lead to weak deflagration explosions and hence to SNe Iax (Kromer et al. 2013;



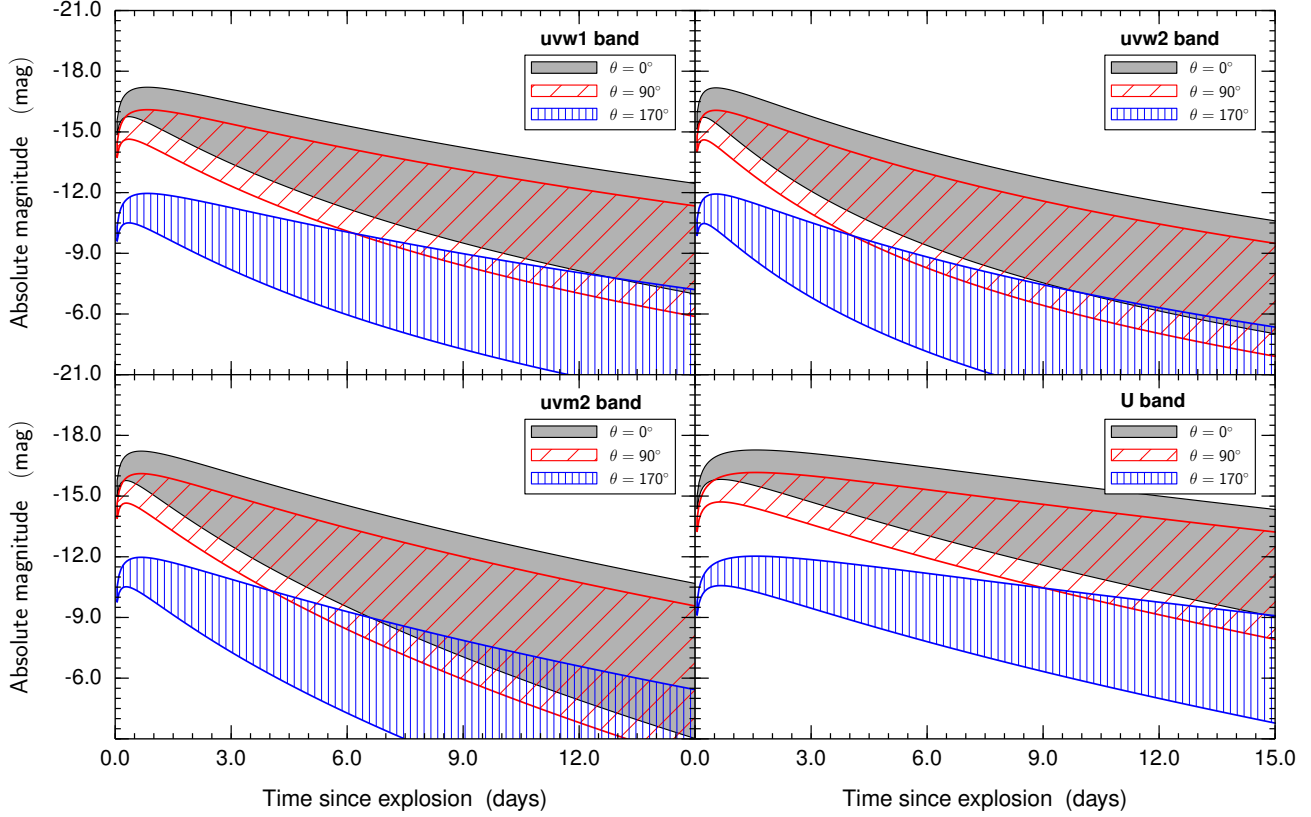
**Figure 2.** Distributions of theoretical light curves predicted from the interaction between SN Ia ejecta and its MS companion star in the four UV bands (*uvw1*, *uvw2*, *uvu2* and *U*) of the *Swift* telescope. Here,  $\theta$  is the viewing angle, the maximum UV flux corresponds to a viewing angle of  $\theta = 0^\circ$  (looking down on the companion star). For a given viewing angle, each shaped region shows the covered magnitude range of our theoretical predictions with the MS donor scenario at different epochs after the SN explosion. We assume the ejecta mass  $M_{\text{ej}} = 1.4 M_\odot$  and the SN explosion energy  $E_{\text{ej}} = 1.0 \times 10^{51}$  erg.

Fink et al. 2014) in that work. In the SD scenario, whether a Chandrasekhar-mass CO WD would finally lead to a subluminal (i.e., Iax events), normal, or overluminous SN explosion, depends on the exact ignition conditions of the CO WD. However, as the WDs in our previous one-dimensional binary evolution calculations (Liu et al. 2015) were treated as point masses, it is impossible to determine the exact ignition conditions of the Chandrasekhar-mass CO WD. Therefore, we cannot distinguish whether the Chandrasekhar-mass CO WD undergoes a delayed-detonation explosion that matches normal SNe Ia or a weak deflagration explosion of SNe Iax, and the progenitor properties at the moment of SN explosions are the same in our BPS calculations for the SD Chandrasekhar-mass scenario. Therefore, we directly use the data obtained from BPS calculations of Liu et al. (2015) to calculate early UV emission of shocked ejecta of SNe Ia in the SD scenario in this work. Here, we only briefly describe our BPS method and basic assumptions, and we refer to Han & Podsiadlowski (2004) for a detailed description about the BPS method used in this work.

We use the Cambridge stellar evolution code STARS (Eggleton 1971, 1972, 1973) to trace the detailed binary evolution of a set of systems consisting of a CO WD and a MS or SG (which is called the MS donor scenario in the following), a RG, or a He star companion. Once the companion star fills its Roche lobe, the mass transfer occurs through Roche-lobe overflow (RLOF) which is treated by the prescription of Han, Tout & Eggleton (2000). Once the WD has accreted the transferred H-rich or He-rich ma-

terial from the companion star and increased its mass to near the Chandrasekhar-mass limit ( $\sim 1.4 M_\odot$ ), we then assume an SN Ia explosion occurs. The optically thick wind assumption of Hachisu, Kato & Nomoto (1996) is used to describe the mass growth of a CO WD by the accretion of H-rich material from the donor star. The prescription of Kato & Hachisu (2004) is implemented for the mass accumulation efficiency onto the CO WDs when He-shell flashes occur. With a series of binary evolution calculations for various close WD binary systems, we determine the initial parameter space leading to SNe Ia in the orbital period–secondary mass (i.e.  $\log_{10} P^i - M_2^i$ ) plane for various initial CO WD masses ( $M_{\text{WD}}^i$ ) in the MS, RG, and He star donor channel.

Furthermore, to obtain the distributions of progenitor properties of binary systems at the moment of SN explosion in the SD scenario, we use a rapid population synthesis code (Hurley, Pols & Tout 2000; Hurley, Tout & Pols 2002) to perform a detailed Monte Carlo simulation. When a binary system evolves to a CO WD + MS (SG, RG, or He star) system and achieves the beginning of the RLOF phase, whether this binary system can lead to a SN Ia explosion is determined by checking if it is located in the SN Ia production regions in the plane of ( $\log_{10} P^i$ ,  $M_2^i$ ) for its  $M_{\text{WD}}^i$  based on our detailed binary evolution. Then, progenitor properties at the moment of SN explosion are obtained by interpolation in the three-dimensional grid ( $M_{\text{WD}}^i$ ,  $M_2^i$ ,  $\log_{10} P^i$ ) of the close WD binaries obtained in our detailed binary evolution calculations. In our BPS calculations, the initial mass function of Miller & Scalo (1979) is used. We assume a circular bi-



**Figure 3.** As Fig. 2, but for the RG donor Chandrasekhar-mass scenario.

nary orbit and set up a constant initial mass ratio distribution (i.e.  $n(q') = \text{constant}$ , see [Goldberg & Mazeh 1994](#); [Bender & Simon 2008](#); [Duchêne & Kraus 2013](#)). The initial separation distribution of [Han, Podsiadlowski & Eggleton \(1995\)](#) is adopted. We assume a constant star formation rate ([Han 2008](#)). The standard energy equations of [Webbink \(1984\)](#) are used to calculate the output of the CE phase. The CE ejection is determined with two highly uncertain parameters,  $\alpha_{\text{CE}}$  and  $\lambda$ . Here,  $\alpha_{\text{CE}}$  is the CE ejection efficiency, i.e. the fraction of the released orbital energy used to eject the CE and  $\lambda$  is a structure parameter that depends on the evolutionary stage of the donor star. In this work, the models with a metallicity of  $Z = 0.02$  and a parameter of  $\alpha_{\text{CE}}\lambda = 0.5$  are adopted ([Han & Podsiadlowski 2004](#)).

### 3 PREDICTIONS OF THE EARLY UV EMISSION

In the analytical model of [Kasen \(2010\)](#), SN ejecta collides with its companion star, the impacting layers are re-shocked and the kinetic energy partially is dissipated, causing UV flux emission from the shock-heated region. This emission dominates the early-time (few days after SN explosion) light curves of SNe Ia within certain viewing angles ([Kasen 2010](#)). At later epochs, this shock flux becomes weak and the light curves of SNe Ia are dominated by the flux of the SN itself. [Kasen \(2010\)](#) analytically estimated the early isotropic bolometric luminosity  $L_{\text{c,iso}}$  by the collision as

(Equation 22 of [Kasen 2010](#))

$$L_{\text{c,iso}} = 10^{43} \left( \frac{a}{10^{13} \text{ cm}} \right) \left( \frac{M_{\text{ej}}}{1.4 M_{\odot}} \right)^{1/4} \left( \frac{v_{\text{ej}}}{10^9 \text{ cm s}^{-1}} \right)^{7/4} \times \left( \frac{\kappa_e}{0.2 \text{ cm}^2 \text{ g}^{-1}} \right)^{-3/4} \left( \frac{t}{\text{d}} \right)^{-1/2} \text{ erg s}^{-1}, \quad (1)$$

where  $a$  is the binary separation at the moment of SN explosion,  $M_{\text{ej}}$  is the SN ejecta mass,  $v_{\text{ej}}$  is the velocity of the SN ejecta colliding with the binary star,  $\kappa_e$  is the electron scattering opacity in the SN ejecta which is assumed to be a constant value in this work, and  $t$  is the time since SN explosion. This luminosity is strongly dependent on the binary separation at the moment of SN Ia explosion. In addition, the effective temperature of the prompt shock emission is estimated as follows (Equation 25 of [Kasen 2010](#)).

$$T_{\text{eff}} = 2.5 \times 10^4 \left( \frac{a}{10^{13} \text{ cm}} \right)^{1/4} \left( \frac{\kappa_e}{0.2 \text{ cm}^2 \text{ g}^{-1}} \right)^{-35/36} \times \left( \frac{t}{\text{d}} \right)^{-37/72} \text{ K}, \quad (2)$$

The strong UV emission at early times from the SN ejecta interacting with the companion star not only strongly depends on the progenitor system but also on the viewing angle  $\theta$  ([Kasen 2010](#)). For a given binary progenitor system, the maximum excess emission should be observed when the viewing angle is  $0^\circ$ , i.e., the companion star lies directly along the line of sight between the observer and the SN explosion. On the contrary, the excess emission detected for viewing angle  $\theta = 180^\circ$  should be negligible, corresponding to a geometry in which the SN Ia lies directly in the line of sight between the observer and the companion star. [Brown et al.](#)

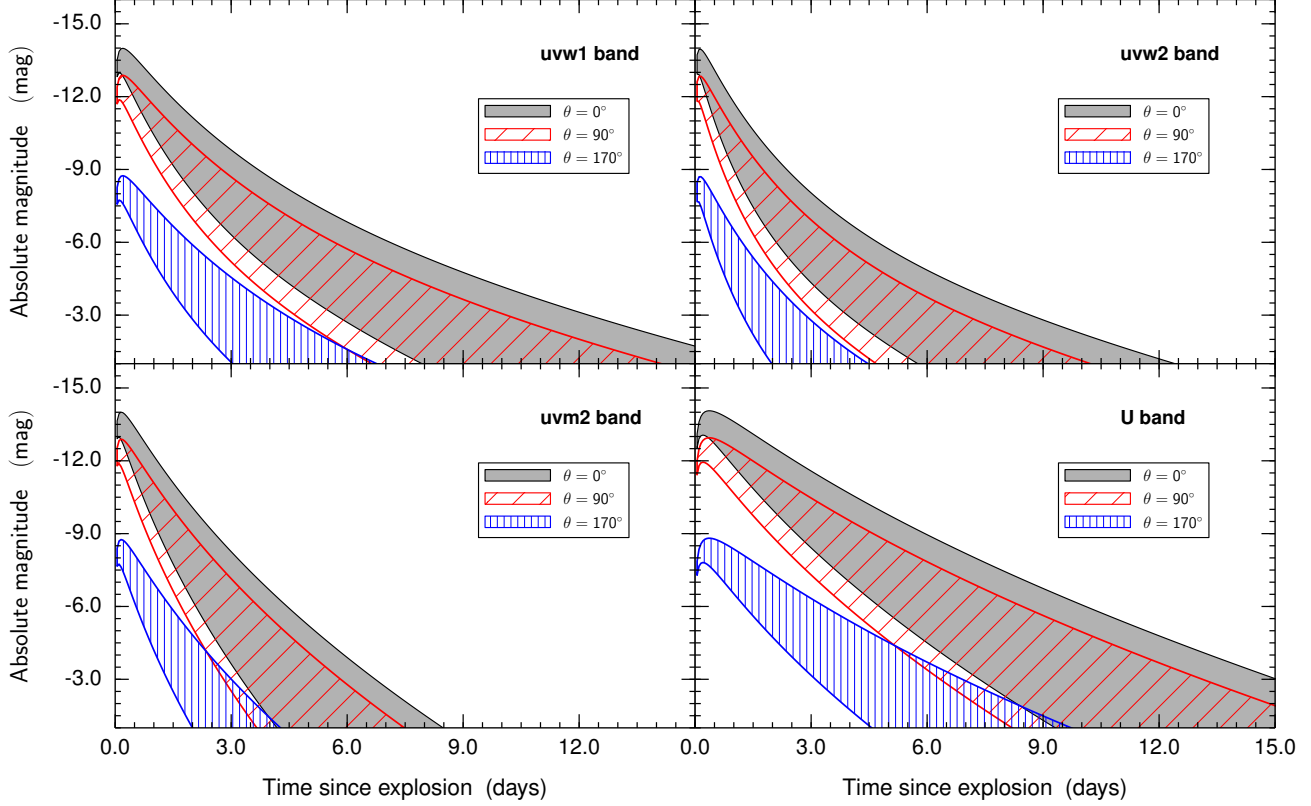


Figure 4. As Fig. 2, but for the He star donor Chandrasekhar-mass scenario.

(2012a) estimated the dependence of the early emission from SN-companion interaction on the viewing angle. They found that the dependence of fractional flux values ( $f$ ) on the viewing angle ( $\theta$ ) can be fitted by a function (Equation 3 of Brown et al. 2012a) of the form:

$$f = (0.5 \cos \theta + 0.5) \times (0.14 \theta^2 - 0.4 \theta + 1), \quad (3)$$

where the viewing angle  $\theta$  is in unit of radians. In this work, we directly adopt this function to calculate the observed flux at different viewing angles for a given epoch.

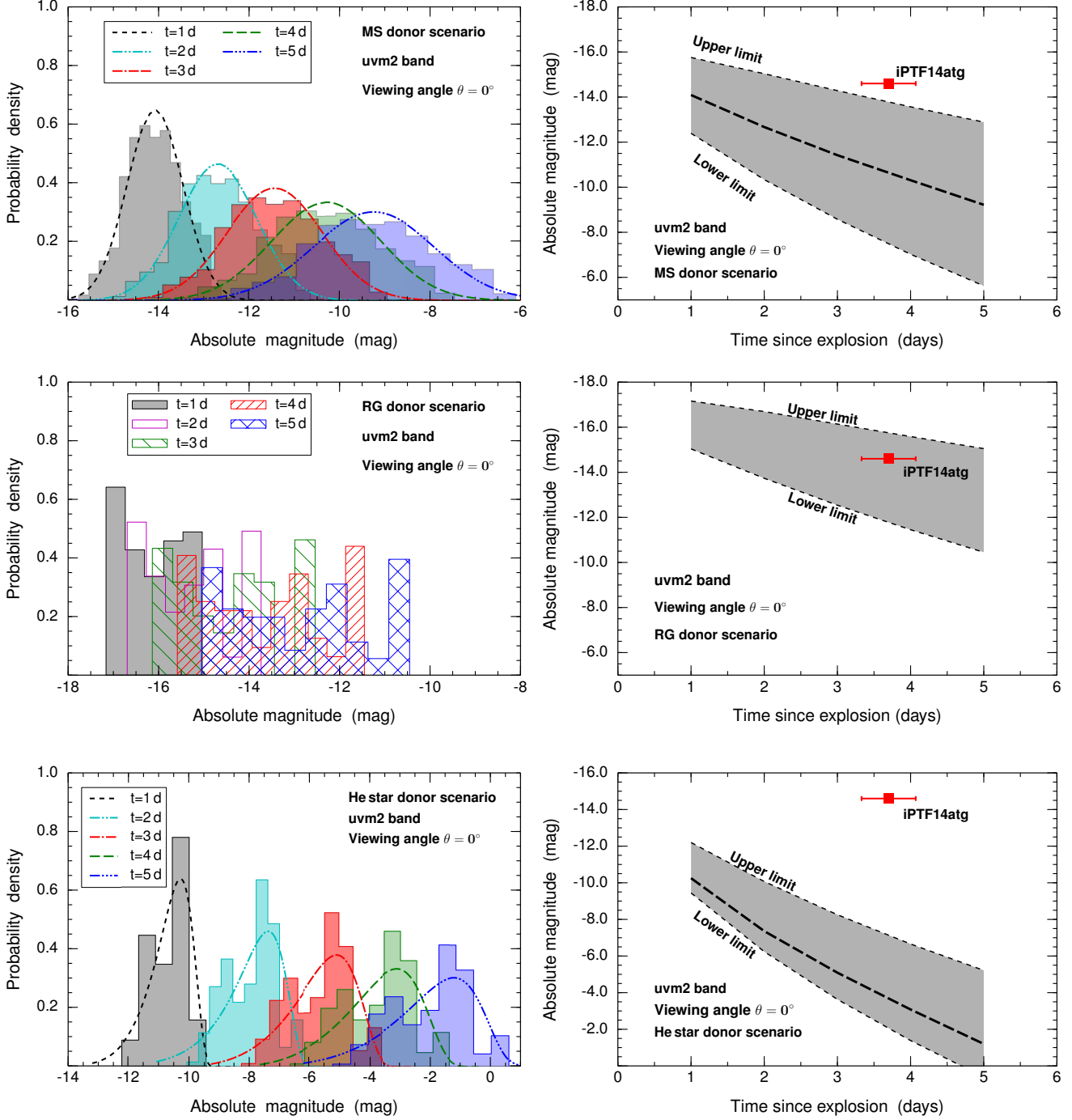
To facilitate direct comparison with the early-time observations of SNe Ia, the early isotropic bolometric luminosity of shocked gas is converted to broad band magnitudes by using the same method as Brown et al. (2012a). Adopting the progenitor properties at the moment of SN Ia explosion obtained from our BPS calculations in Section 2, we create a set of blackbody models under a given viewing angle with appropriate temperature and luminosity based on Equations 1, 2 and 3. In Fig. 1, we present the distributions of binary separation at the moment of SN explosion in our BPS calculations for three different SD progenitor scenarios. It is shown that most progenitor systems in the He star donor scenario have a relatively small separation (less than  $10^{11}$  cm) at the moment of SN explosion, and the binary systems in the H-rich donor scenario cover a separation range of about  $10^{11} - 4.0 \times 10^{12}$  cm. With the created blackbody models, we then calculate the synthetic magnitudes at different bands by using transmission curves of chosen filters. Specifically for this work, the *Swift*/UVOT filter system and their corresponding transmission curves are selected. The absolute magnitudes are calculated in the AB magnitude system.

With different donor star models, the theoretical distributions

of UV emission at early times from SN ejecta-companion interaction in the SD scenario are presented in Figs. 2, 3 and 4. Here, we assume typical explosion parameters of an SN Ia, i.e., the amount of ejecta mass  $M_{\text{ej}} = 1.4 M_{\odot}$  and the SN explosion energy  $E_{\text{ej}} = 1.0 \times 10^{51}$  erg. These typical values lead to a mean expansion velocity of SN ejecta of  $\approx 10^4 \text{ km s}^{-1}$ . Here, only four different *Swift*/UVOT filters are chosen to show as examples, i.e., the *uvw1*, *uvw2*, *uvw2* and *U* bands (the *B* and *V* band are not included), because the excess emission at early times should be brightest in the UV and become subordinate at longer optical wavelengths (Kasen 2010; Brown et al. 2012a). For a given viewing angle, we show the upper-limit and lower-limit absolute magnitude in each band as a function of time since the SN explosion. It is shown that the theoretical UV luminosities of shocked gas in the MS donor scenario cover a relatively wider magnitude range because binary systems in this scenario have a wide range of progenitor properties at the moment of SN explosion compared to those in other two donor scenarios (Fig. 1). In addition, the early UV luminosities in the He star donor scenario are much weaker than those of the H-rich scenario by more than three magnitudes because He star donor progenitor systems have closer separations (Fig. 1) when the WDs grow to the Chandrasekhar-mass limit (Fig. 4). We note that the explosion parameters of typical SNe Ia used here may not match the case of iPTF14atg because it is identified as a subluminous SN 2002es-like event (see Section 4.1), which however, strongly depends on the exact explosion mechanism of a Chandrasekhar-mass CO WD.

In Figs. 2–4, we present possible magnitude ranges that can be covered by the early UV luminosities arising from the ejecta-companion interaction in different SD progenitor scenarios. To better compare our predictions with early-time UV observations of





**Figure 5.** Left: the probability distribution of the absolute magnitudes of shocked gas in *uvm2* band at different epochs after the SN Ia explosion for the MS (top), RG (middle) and He star (bottom) donor scenario, respectively. The fitting curves of the distributions are also plotted except for the RG donor scenario. Right: comparison between the early observations of a peculiar SN Ia iPTF14atg and our predictions. The boundaries (short thin dashed curves) of gray region correspond to the upper-limit and lower-limit magnitude in *uvm2* band. The long bold dashed lines show absolute magnitudes at the peaks of fitting curves of corresponding figures in left panel. The location of the early UV flash detected in iPTF14atg (Cao et al. 2015) is shown with the square in red simply assuming 10% error of the time because of the uncertainty of the explosion date.

SNe Ia and put stronger constraints on the possible progenitors of SNe Ia, the probability distributions of our predicted UV luminosities at a given epoch after the SN explosion are further shown in Fig. 5. Here, we only consider the case with a viewing angle  $\theta = 0^\circ$ , i.e., the maximum flux case, and the results at *uvm2* band are chosen to give an example because *uvm1* and *uvm2* filters have

an extended red tail. The distributions of different viewing angles and other bands can be roughly estimated according to the results in Fig. 2 to Fig. 5. Also, only the results within the first five days after the SN explosion are presented in Fig. 5 because SN light curves at late times are dominated by the flux from the SN itself (Kasen 2010). As it is shown in Fig. 5, a peak is clearly seen in the proba-

bility distributions of the MS and He star donor scenario. However, the probability distributions of absolute magnitudes within a given day in the RG scenario is relatively flat (Fig. 5). This may indicate that early UV luminosities of different progenitor systems in the RG donor scenario have a similar probability at a given epoch after SN explosion.

## 4 DISCUSSIONS

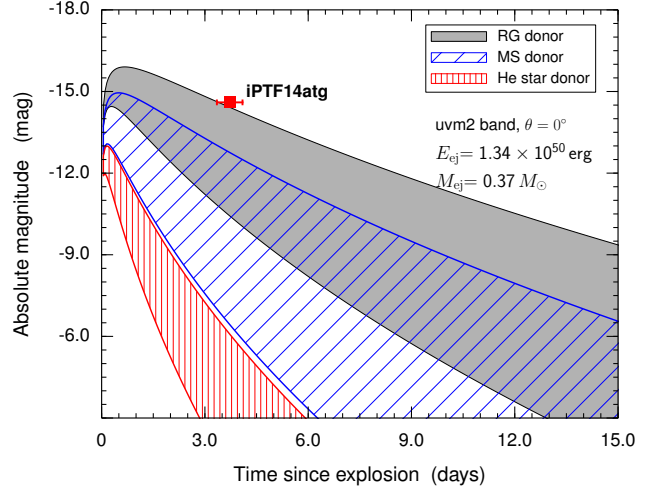
### 4.1 Comparison with the early UV flash of iPTF14atg

A strong UV pulse in the early-time light curves of a subluminal SN Ia iPTF14atg has been detected by Cao et al. (2015). They further suggested that this strong UV pulse supports that some SNe Ia arise from the SD Chandrasekhar-mass scenario. Comparing their observations to analytical models of Kasen (2010), they found that the theoretical UV emission from shocked ejecta of a binary system with a separation of about  $60 R_{\odot}$  can match the observations assuming the explosion energy  $E_{\text{ej}} = 10^{51}$  erg and ejecta mass  $M_{\text{ej}} = 1.4 M_{\odot}$ . Here, we also compare the predictions from our BPS calculations for different SD scenarios to the early UV flash of iPTF14atg to put a more stringent on the possible progenitor of this event.

A detailed comparison with the results of the *uvm2* band is given in the right column of Fig. 5. It shows that the observed early UV pulse of iPTF14atg is stronger than the upper limit of the theoretical UV luminosity predicted from the MS donor and He star donor scenario at the same epoch (Fig. 5). Considering that the actual viewing angle may be larger than  $\theta = 0^{\circ}$  and taking the uncertainties on the explosion parameters (see Section 4.4) into account, it is unlikely that the detected UV flash in early-time light curves of iPTF14atg arises from the interaction of SN Ia ejecta with a MS or He star companion. However, our theoretical early UV luminosities from the RG donor scenario can include the early UV flash of iPTF14atg (Fig. 5) although the theoretical upper-limit luminosity in this scenario can still decrease to a value weaker than the observed UV flash in iPTF14atg as the viewing angle increases. Therefore, whether the predictions from the RG donor scenario can support the early UV observations of iPTF14atg depends on the actual viewing angle of the observations. Nevertheless, we still suggest that the RG donor binary system as progenitor of iPTF14atg is more possible if the early UV flash detected in an SN 2002es-like SN iPTF14atg indeed arises from the ejecta-companion interaction in the SD scenario.

#### 4.1.1 Different explosion parameters

The comparisons given above are based on an assumption of the typical SN Ia explosion parameters as those used in Cao et al. (2015). However, it has been suggested that iPTF14atg is more likely to belong to the subluminal SN 2002es family by Cao et al. (2015). Meanwhile, it is shown that the peak magnitude of iPTF14atg is similar to SN 2005hk (a typical SN Iax event). The hydrodynamical simulations of Kromer et al. (2013) have shown that the off-centre-ignited weak deflagration of Chandrasekhar-mass CO WDs is able to reproduce the characteristic observational features of SN 2005hk quite well. Adopting the weak deflagration explosion model ( $E_{\text{ej}} = 1.34 \times 10^{50}$  erg and  $M_{\text{ej}} = 0.37 M_{\odot}$ , which corresponds to a mean expansion velocity  $v_{\text{ej}} \approx 6000 \text{ km s}^{-1}$ ) of Kromer et al. (2013) as inputs of the analytical model of Kasen (2010), we predict theoretical early UV luminosities in the *uvm2*



**Figure 6.** Similar as Fig. 2, but for theoretical predictions of SN Iax case. Here, only a viewing angle  $\theta = 0^{\circ}$  and *uvm2* band are considered. The ejecta mass ( $M_{\text{ej}} = 0.37 M_{\odot}$ ) and SN explosion energy ( $E_{\text{ej}} = 1.34 \times 10^{50}$  erg) are directly derived from a weak deflagration explosion of the Chandrasekhar-mass C/O WD for SN Iax event (Kromer et al. 2013). The location of early UV flash of iPTF14atg is also shown (Cao et al. 2015).

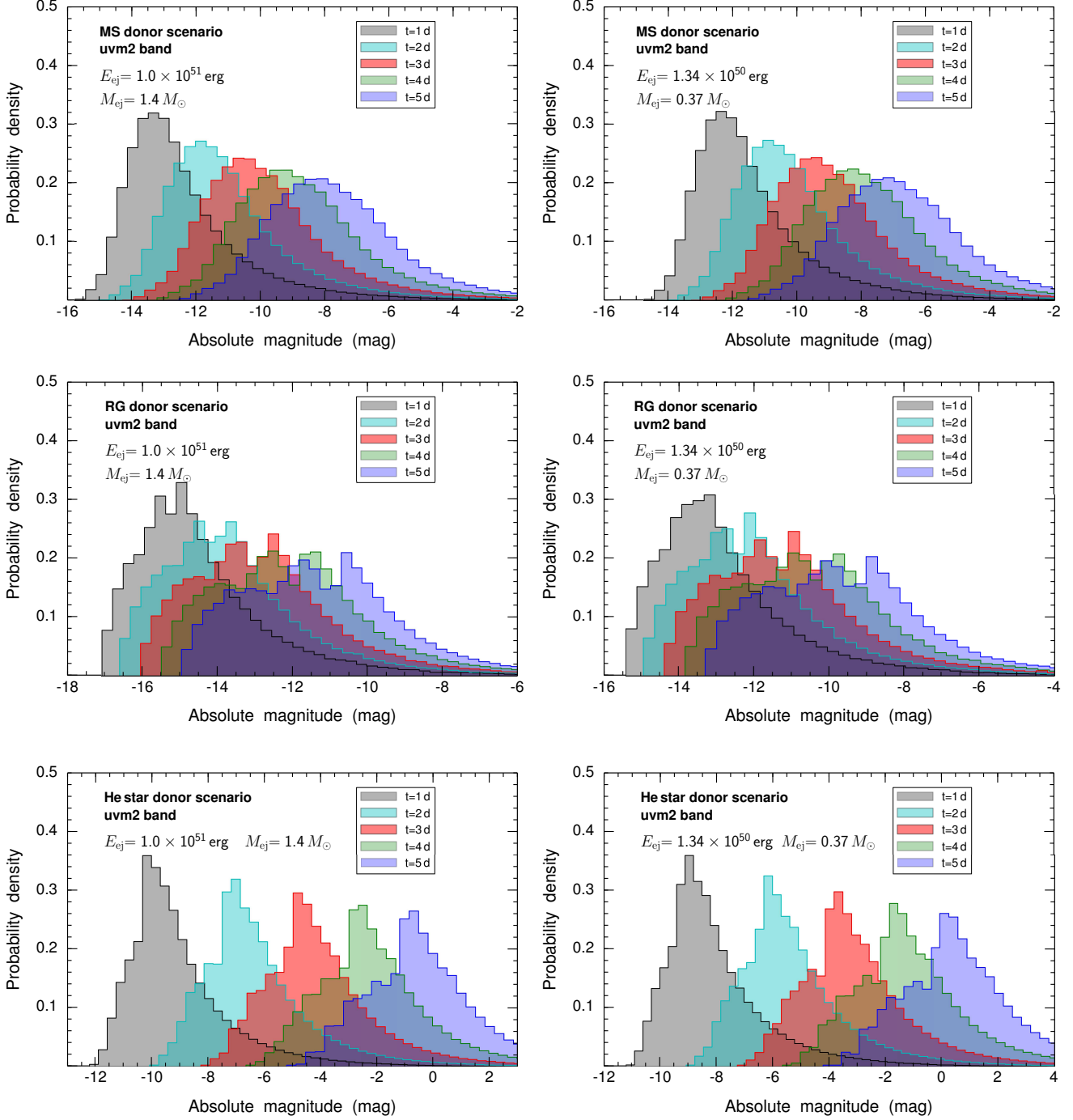
band of different SD progenitor scenarios (Fig. 6). Compared to the results with typical explosion parameters in Figs. 2–4, it is shown that the early UV luminosities of shocked ejecta are weaker by about one magnitude when the explosion parameters of Iax events are used (Fig. 6). If the SN iPTF14atg was produced from an explosion model that has similar explosion parameters with the weak deflagration explosion model for SNe Iax in Kromer et al. (2013), the observed UV flash in iPTF14atg is a bit stronger than the upper-limit luminosity of our RG donor model at similar epoch (Fig. 6).

However, the actual explosion date was not well constrained in Cao et al. (2015). Therefore, the delay time between the SN explosion and the moment of ejecta-companion interaction happens is not well determined, which means that the location of early UV pulse of iPTF14atg in Figs. 5 and 6 can be shifted a bit towards the left (or the right) if the actual explosion date is earlier (or later) than that used in Cao et al. (2015).

#### 4.1.2 SN birth rate

In our BPS calculations, we obtain a SN Ia rate of about  $3 \times 10^{-5} \text{ yr}^{-1}$  (i.e., three SN Ia events every  $10^5$  years) in the RG donor channel for a constant star formation rate ( $5.0 M_{\odot} \text{ yr}^{-1}$ ), which is about 1% of the total SN Ia rate if we assume that the total SN Ia rate is  $3.5 \times 10^{-3} \text{ yr}^{-1}$  based on the inferred Galactic SN Ia rate of  $3 - 4 \times 10^{-3} \text{ yr}^{-1}$  (Cappellaro & Turatto 1997). Observationally, Ganeshalingam et al. (2012) estimate that roughly 2.5% of SNe Ia may belong to SN 2002es-like events within a fixed volume. The birth rate from the RG donor channel in our BPS calculation is roughly comparable with observed rate of SN 2002es-like event (but see Hachisu et al. 1999). In addition, the delay times between star formation and SN explosion in the RG donor scenario are quite long ( $\gtrsim 3 \text{ Gyr}$ ), which seems to support the fact that 2002es-like SNe Ia are likely from an old stellar population (Ganeshalingam et al. 2012) and the host galaxy of iPTF14atg is classified as an old galaxy.

However, the contribution of the RG donor scenario to the total SN Ia rate is quite uncertain (Hachisu et al. 1999;



**Figure 7.** Similar to Fig. 5, but showing the results with a random distribution of viewing angle  $\theta$ . The distributions by adopting the explosion parameters for typical SNe Ia (left column) and SN Iax event (right column) are presented.

Han & Podsiadlowski 2004; Chen, Han & Tout 2011). If mass transfer in symbiotic binaries (RG donor model) occurs through the stellar wind rather than the RLOF assumed in this work (Branch et al. 1995), the SN contribution from this scenario could remarkably increase and binary systems could have much larger orbital separations than those in this work at the moment of SN Ia explosion (Chen, Han & Tout 2011). Subsequently, early UV emissions from shocked gas may be much stronger than those obtained from our RG donor models.

## 4.2 The effect of viewing angle

In Fig. 5, we present the expected magnitudes in the *uvm2* band from a fixed viewing angle ( $\theta = 0^\circ$ ). However, we do not necessarily observe the interaction from  $\theta = 0^\circ$ . To investigate the effect of the viewing angle on the observational magnitude, we randomly assign the viewing angle and obtain the probability distribution for the observational magnitude in the *uvm2* band. Fig. 7 shows the probability distribution for both normal SNe Ia (i.e.  $E_{\text{ej}} = 1.0 \times 10^{51}$  erg and  $M_{\text{ej}} = 1.4 M_\odot$ ) and SN Iax events (i.e.



$E_{\text{ej}} = 1.34 \times 10^{50}$  erg and  $M_{\text{ej}} = 0.37 M_{\odot}$ ). Comparing to the distributions in Fig. 5, the peak of the distribution becomes about one magnitude fainter after taking the effect of the viewing angle into account. However, the maximum magnitude achieved by the SN ejecta-companion interaction does not change and our conclusion regarding the SN iPTF14atg remains unaltered.

### 4.3 The Spin-up/Spin-down model

In the SD scenario, a WD accretes and retains companion matter that carries angular momentum. As a consequence the WD spins with a short period which leads to an increase of the critical explosion mass. If the critical mass is higher than the actual mass of the WD, the SN explosion can only occur after the WD spins down to decrease its critical explosion mass to fall below the current mass of the WD with a specific spin-down timescale (Di Stefano, Voss & Claeys 2011; Justham 2011; Hachisu et al. 2012). In such case, the MS or RG donor star might shrink rapidly before the SN Ia explosion occurs because most its H-rich envelope has been exhausted during a long spin-down phase of the rapidly rotating WD. As a result, the early UV signature from SN Ia ejecta interacting with its companion star should be remarkably reduced compared to the results we presented in this work because the donor star is much smaller than its Roche lobe at the moment of SN Ia explosion. In addition, as previously mentioned, this “spin-up/spin-down” model seems to be able to explain the lack of H in late spectra of SNe Ia and possibly the absence of a surviving companion star in the SN remnants (Di Stefano, Voss & Claeys 2011; Justham 2011; Hachisu et al. 2012). However, the exact spin-down timescale of the WD in this model is quite unknown.

### 4.4 The effect of different explosion models

In the SD scenario, depending on the exact ignition condition, a Chandrasekhar-mass CO WD can undergo a deflagration, a detonation, or a delayed detonation explosion (Arnett 1969; Woosley, Taam & Weaver 1986; Khokhlov 1989; Röpke & Hillebrandt 2005; Röpke et al. 2007), which could finally produce SN Iax events (Jordan et al. 2012a; Kromer et al. 2013, 2015; Fink et al. 2014), normal SNe Ia (Seitenzahl et al. 2013), or overluminous SNe Ia (Plewa, Calder & Lamb 2004; Jordan et al. 2012b). The distributions of early UV emission of shocked gas in normal SNe Ia and Iax events have been presented in Sections 3 and 4.1.

By analytically deriving the existence of a characteristic length scale which establishes a transition from central ignitions to buoyancy-driven ignitions, Fisher & Jumper (2015) suggested that the Chandrasekhar-mass WDs in the SD scenario are generally expected to explode as overluminous SNe Ia rather than normal SNe Ia or Iax events. If the suggestion of Fisher & Jumper (2015) is true, early UV signatures due to the ejecta-companion interaction may be easier to be detected in overluminous SNe Ia because overluminous SNe Ia may have a higher explosion energy than that of normal SNe Ia. A higher explosion energy is expected to cause stronger early UV emissions of shocked gas for a given binary progenitor.

### 4.5 Model uncertainties

The prescription of the optically thick wind model of Hachisu, Kato & Nomoto (1996) and He-retention efficien-

cies from Kato & Hachisu (2004) are used to describe the mass accumulation efficiency of accreting WDs in our detailed binary evolution in this work. However, different mass-retention efficiencies may lead to the results that are different from our BPS calculations (e.g., see Bours, Toonen & Nelemans 2013; Piersanti, Tornambé & Yungelson 2014; Ruiter et al. 2014; Toonen et al. 2014). However, the exact mass-retention efficiency is still not well-constrained.

It should be kept in mind that the initial conditions of BPS calculations such as the CE evolution, current star-formation rate and initial mass function, may be sensitive to the assumed parameters in specific BPS codes, which lead to some uncertainties on the BPS results (Toonen et al. 2014). However, current constraints on these parameters (e.g., the CE efficiency, see Zorotovic et al. 2010; De Marco et al. 2011; Ivanova et al. 2013) are still weak. For a detailed discussion for the effect of different theoretical uncertainties, see Claeys et al. (2014).

Finally, we point out that the analytical model of Kasen (2010) is simple, which may lead to the predicted early UV luminosity being overestimated, or underestimated. For instance, a constant opacity from electron scattering is assumed in the analytical model of Kasen (2010), the luminosity can be reduced if the realistic opacity in the interacting material is decreased (Brown et al. 2012a). To put stronger constraints on the possible progenitor of SNe Ia, the radiation hydrodynamical simulations of the interaction between SN Ia ejecta and its companion star are encouraged to address in the future study.

## 5 CONCLUSION AND SUMMARY

In the SD Chandrasekhar-mass scenario of SNe Ia, strong UV emissions arising from the SN ejecta interacting with its companion star is suggested to be dominant in the early-time light curves of SNe Ia (Kasen 2010). These prompt UV emission characteristics are expected to constrain possible progenitor systems of SNe Ia. In this work, we perform BPS calculations for different progenitors of SNe Ia within the SD Chandrasekhar-mass scenario to obtain progenitor properties at the moment of SN Ia explosion. We then predict the distributions of early-time UV luminosities of SN ejecta-companion interaction of different progenitors by combining our BPS results with the analytical model of Kasen (2010). These theoretical predictions for early UV emissions of shocked ejecta will be helpful to compare with future early-time observations of SNe Ia to put constraints on their possible progenitors.

In addition, assuming the observed strong UV pulse of iPTF14atg indeed arises from the SN ejecta-companion interaction, we have compared our theoretical UV luminosities to the observed UV pulse at early times of a peculiar subluminous SN Ia iPTF14atg (Cao et al. 2015). With our BPS models, we find that predicted UV luminosities in the MS and He star donor scenario struggle to reach an upper-limit absolute magnitude as strong as early UV flash observed in iPTF14atg, which suggests that the MS and He star donor binary systems are unlikely to be the progenitor. In particular, the He star donor binary system as progenitor of SN iPTF14atg can be ruled out by our population synthesis calculations. However, theoretical UV luminosities at early times in our RG donor scenario provide a match with the early UV observations of iPTF14atg under some appropriate conditions such as a favorable viewing angle. Therefore, we suggest that a red-giant donor binary system as the progenitor of an SN 2002es-like peculiar SN Ia iPTF14atg is more possible based on our populations synthesis model.

## ACKNOWLEDGMENTS

We thank the anonymous referee for his/her valuable comments and suggestions that helped to improve the paper. Z.W.L thanks Bo Wang for his helpful discussions about BPS calculations. We would also like to thank Carlo Abate and Norberto Castro for their helpful discussions. This work is supported by the Alexander von Humboldt Foundation. R.J.S. is the recipient of a Sofja Kovalevskaja Award from the Alexander von Humboldt Foundation. T.J.M. is supported by Japan Society for the Promotion of Science Postdoctoral Fellowships for Research Abroad (26-51).

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